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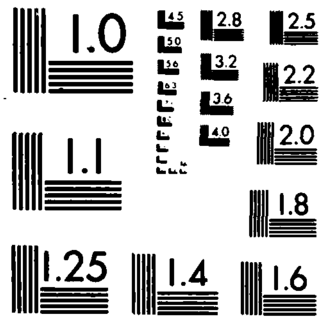

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THE DEVELOPMENT OF A HIGH SPEED EXPONENTIAL FUNCTION GENERATOR FOR LINEARIZATION OF MICROWAVE VOLTAGE CONTROLLED OSCILLATORS (U)

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THE DEVELOPMENT OF A HIGH SPEED EXPONENTAL FUNCTION GENERATOR FOR LINEARIZATION OF MICROWAVE VOLTAGE CONTROLLED OSCILLATORS (U)

by

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ABSTRACT

Voltage Controlled Oscillators used in radar signal simulators usually employ piecewise approximation linearizers to compensate for non-linear frequency versus voltage tuning characteristics. A linearizer was developed which closely approximates an exponential (frequency/voltage) relationship found in many VCO's. This linearizer uses the forward biased (voltage/current) characteristic of a p-n junction to provide exponential linearization in a simple, thermally-stable, wide band circuit.

RÉSUMÉ

Les oscillateurs à tension variable couramment employés pour la simulation de signaux de radars utilisent habituellement un circuit de linéarisation par point pour compenser leur réponse non linéaire tension versus fréquence. On développa donc un circuit de linéarisation qui se rapproche trés près de la courbe exponentielle (fréquence/tension) que l'on retrouve chez plusieurs oscillateurs. Ce circuit, d'une grande largeur de bande, utilise la caractéristique (tension/courant) du biais avant d'une jonction P-N pour générer la réponse exponentielle requise pour la linéarisation.

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LIST OF FIGURES

1.0 INTRODUCTION

Voltage Controlled Oscillators (VCO) are used in low power radar signal simulators to produce programmable signal scenarios. Providing coincident pulses are not required, one VCO can generate a large number of classes of radar signals using microprocessor and discrete hardware to obtain fast execution. For each emitter pulse, the oscillator is quickly tuned to the required frequency and the signal is switched to the output for the duration of the pulse. Simulation of pulse compression emitters can be effected by applying a linear analog ramp to the tuning input of the VCO. During the pulse duration the ramp continuously changes the VCO frequency, thereby causing a "chirp" signal.

A VCO should provide a frequency set-on accuracy of about 0.05% of carrier frequency and respond to the tuning voltage demand in a few microseconds.

Commercial VCO's usually consist of a varactor-tuned, microwave, frequency source and a non-linear voltage amplifier called a linearizer. The linearizer compensates for the non-linear voltage versus frequency function of the oscillator to achieve an approximate linear relationship. The linearizer is based on a straight line approximation technique and is often found to ring in response to a tuning voltage step thereby causing long settling times.

Measurements on the oscillator alone indicated that in many cases the required input versus output voltage function of the linearizer is exponential in nature, therefore an exponential function could be employed as a linearizer. Also the exponential function is continuous compared to that of the straight line approximator. Therefore, for chirp signals, a more gradual frequency slope could be obtained which eliminates spurious responses at the break points of a linear approximator.

This report deals with the development of the exponential function generator and concludes with measurements on accuracy and temperature stability.

2.0 VCO CHARACTERISTICS

Before consideration is given to various techniques to linearize a VCO, it is necessary to determine the VCO tuning voltage versus frequency function. As outlined in Appendix A, a microcomputer was used to step the tuning voltage through all possible values, and for each value, the resultant frequency of the VCO was measured using a frequency counter. Such a measurement is shown in Figure 1 for an X band VCO. The desired response, of course, is the indicated straight line.

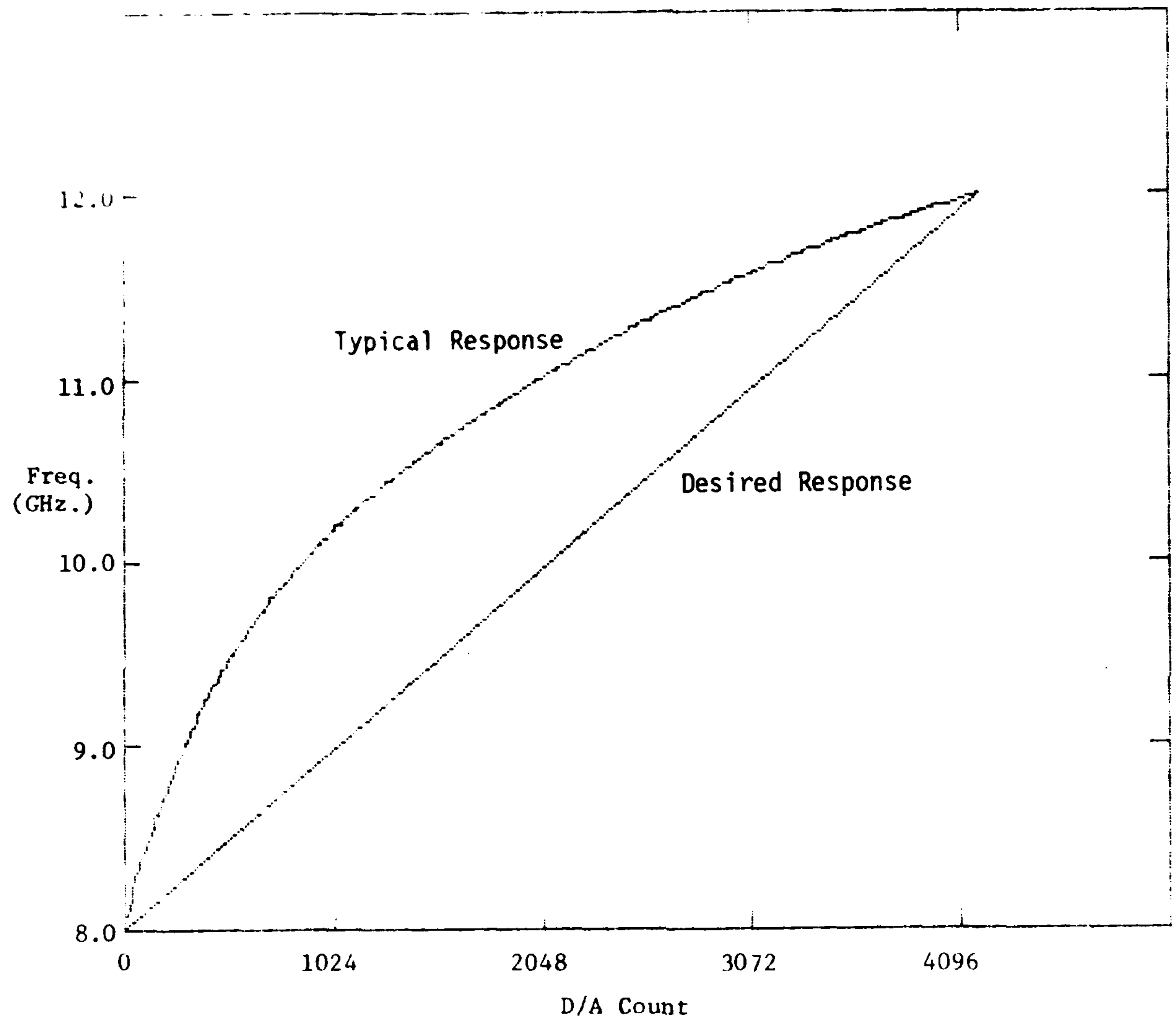


Fig. 1 Non-linearized VCO Transfer Function

Since a linearizer module would be inserted between the tuning voltage source and the tuning input to the VCO, the combined function of the linearizer and VCO can be written as:

$$F = G\ [h(v)] \qquad (1)$$

where: h(v) is the gain characteristic of the linearizer and G is the VCO function, for example, that presented in Figure 1.

From equation 1, it is clear that the inverse of G, will yield h(v), the required linearizer function. The required linearizer function shown in Figure 2 was derived from the data plotted in Figure 1 by using an inversion algorithm. Note the frequency range 8-12 GHz is replaced by 4096 count, (C), values, as described in Appendix A.

2.1 Linearization Methods

Typically, the curve of Figure 2 is approximated by several linear segments using analog circuitry. However, in order to achieve a reasonable accuracy, a considerable number of segments are required.

It is also apparent that for a large number of segments (10 or more), complex circuitry will result. In radar EW simulators, it is also required that the tuning speed be high (less than 5 microseconds), and hence the complex circuit must also have fast rise and settling times.

From measurements taken on a commercial linearizer delivered with a VCO module, the bandwidth was measured to be 100 KHz and the settling time was observed to be of the order of 100 microseconds due to a ringing effect.

Stimulated by the above mentioned problems, it appeard that the curve of Figure 2 could possibly be approximated by an exponential function of the form:

$$V_o = a\ (\exp(b\ V_i)-1) \qquad (2)$$

where: V_i is the input voltage to the linearizer
a and b are constants
and V_o is the output voltage of the linearizer.

As outlined in Appendix B, the constants can be found numerically and the resultant exponential linearizer function is plotted over the required function as shown in Figure 3. It is evident that a good fit was obtained because it is almost impossible to delineate between the experimental and theoretical curves.

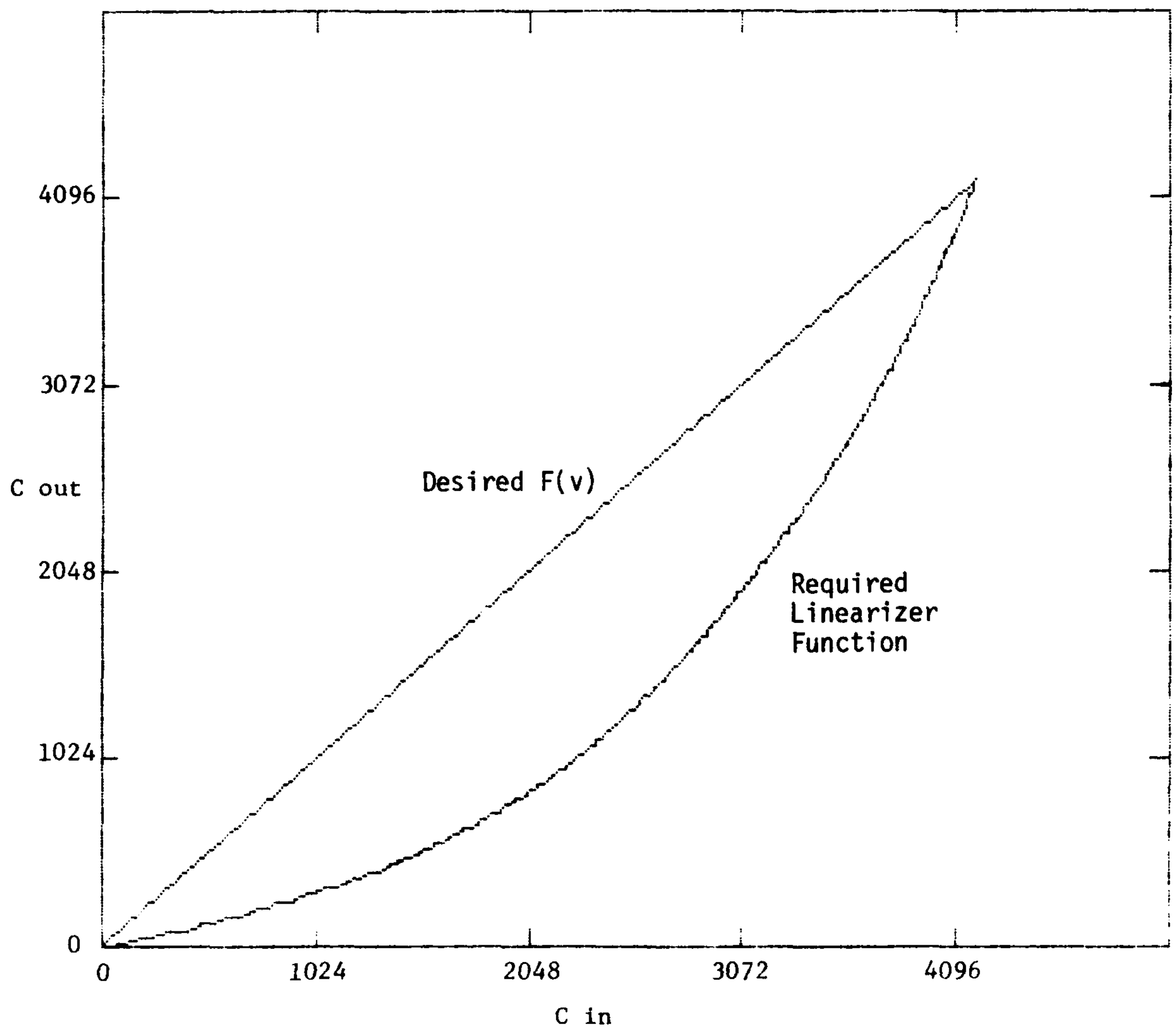


Fig. 2 Required Linearizer Transfer Function

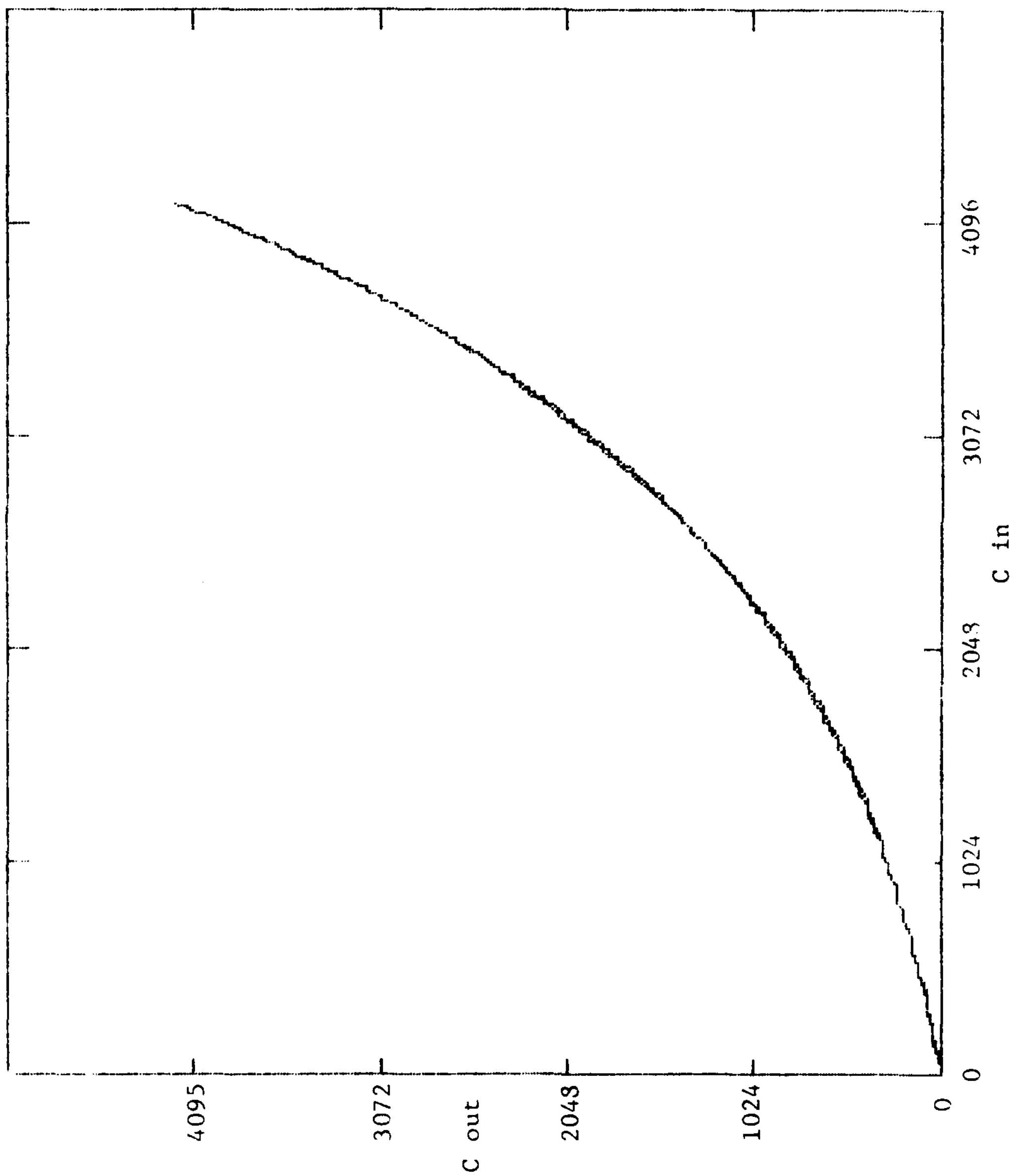


Fig. 3 Theoretical Fit

The final step, however, is to consider the response of the linearizer and VCO modules together as a system. Substituting equation 2 into equation 1, and using the measured data set for the VCO function (G in equation 1), the desired linearized VCO function can be obtained and is shown plotted over the ideal straight line function in Figure 4. Figure 5 details the error versus frequency one might hope to achieve where the maximum deviation is about 30 MHz.

2.2 Exponential Linearizer Circuit Realization

The exponential function is based on the non-linear property of a semiconductor diode where the current/voltage relationship is given by:

$$i = i_o \left(\exp(v/(n\,V_t)) - 1\right) \qquad (3)$$

where: i_o is the reverse leakage current of the diode

v is the voltage applied across the junction

n is 2 for silicon

and $V_t = T/11{,}600$

where: V_t is the "volt equivalent of temperature"

T is the temperature in degrees Kelvin.

In the conceptual circuit of Figure 6, Q1 is the non-linear element given by equation 3 where the base-emitter current i is multiplied by the current gain of the transistor. The other components in Figure 6 perform inversions and current to voltage transformations to achieve the function given in equation 2. Appendix C provides details on the derivation of the circuit form, and given a set of equations for the circuit values, an exact circuit is realized.

2.3 Temperature Dependence

As noted from equation 3, the linearizer will be temperature dependent. In the actual realization, the transistor pair, Q1 and Q2 were selected to be on a single substrate. The substrate was pre-heated to a regulated temperature using other spare transistors on the array.

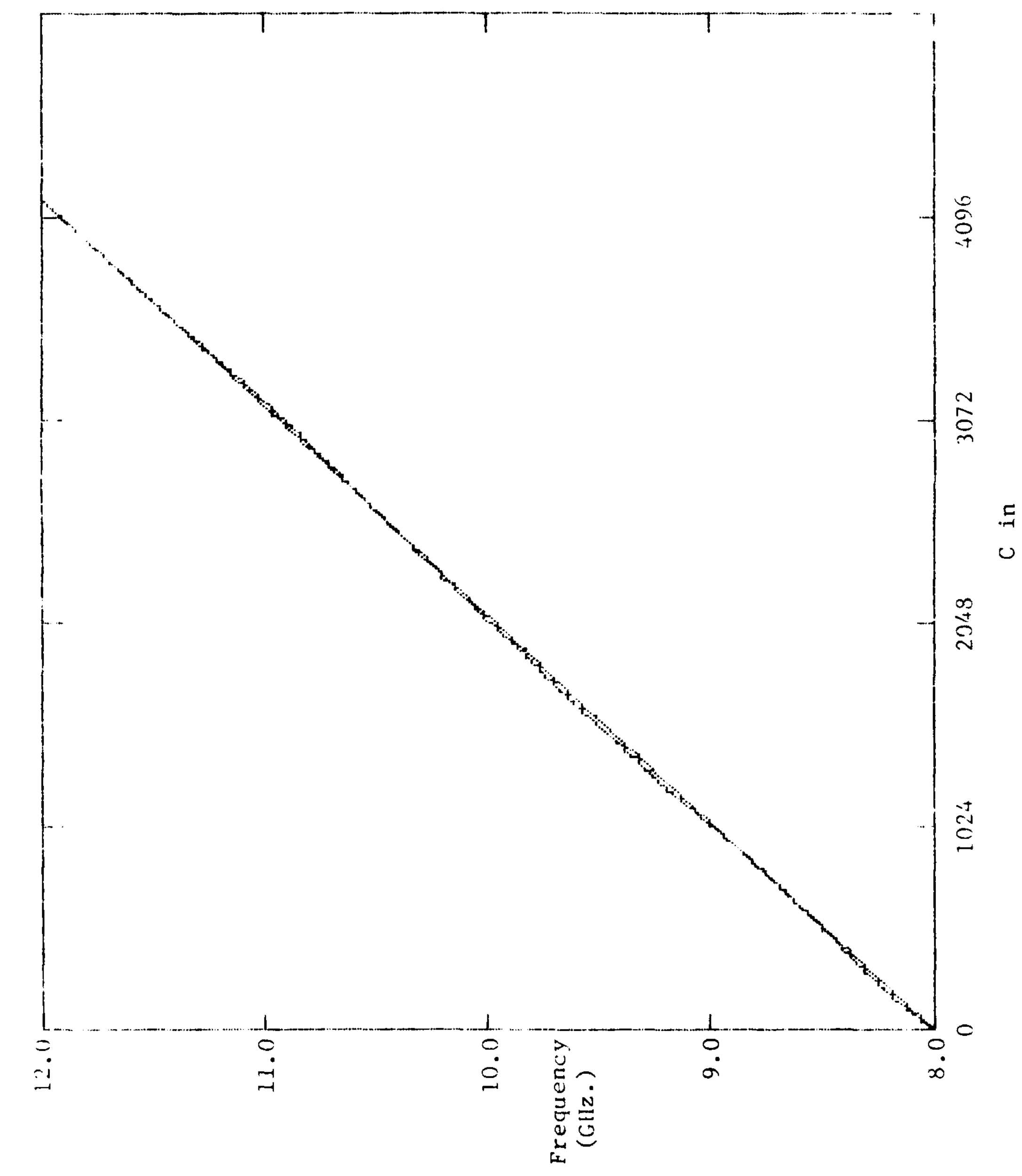


Fig. 4 System Exponential Fit

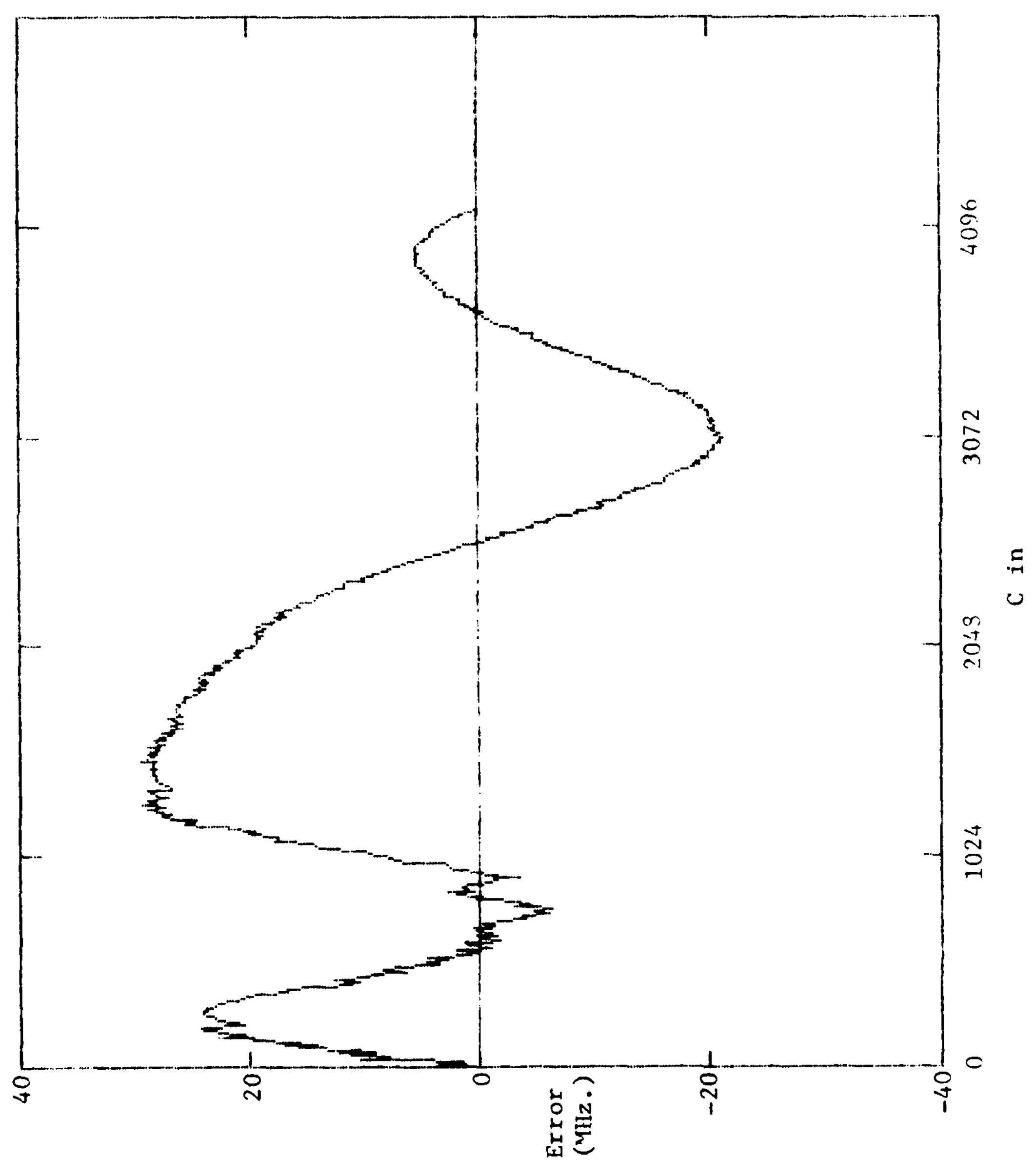


Fig. 5 System Error

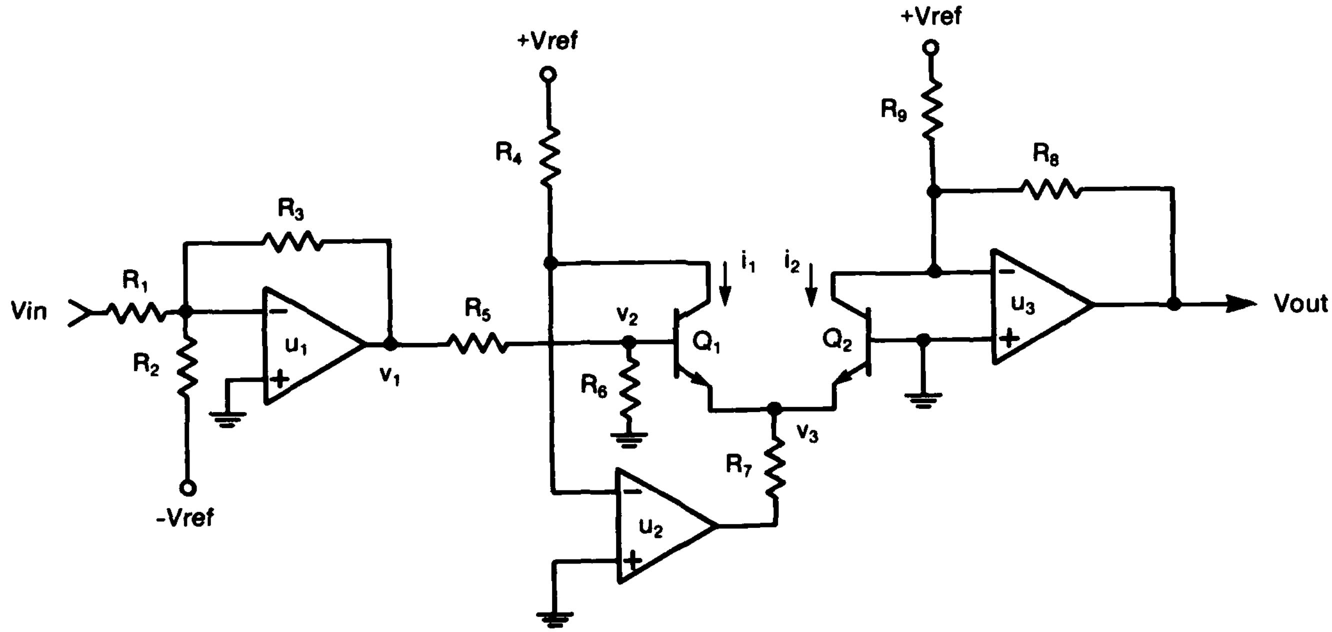


Fig. 6 Conceptual Exponential Function Generator

3.0 EXPERIMENTAL RESULTS

The performance of the exponential linearizer can be evaluated on the basis of an analysis of the system function (frequency versus input voltage) data, long term frequency stability data and the response of the linearizer to a voltage step input. The following sections deal with these measurements.

3.1 System Function Measurement

The system function (linearizer and VCO combined) was determined by acquiring a group of 4096 voltage-frequency data values as shown in Figure 7 together with the linear function. Figure 8 shows the difference or error between the experimental results and an ideal linear function indicating a +/- 100 MHz deviation, or about 1% error.

3.2 Long Term Frequency Stability

Long term Frequency stability was measured using 5 selected tuning voltage values which were recorded in a burst with 50 msec between each successive value. The burst recording was made every 15 minutes for approximately 75 hours. The graphs shown in Figures 9 to 13 indicate the frequency drift for each of the selected tuning voltages. The maximum frequency drift is approximately 4 MHz over 75 hours evaluation period.

3.3 Linearizer Step Response

Measurements were made on the response of a 100 KHz bandwidth commercial linear approximator and the exponential function linearizer. Figure 14a shows the response of the linear approximator to a step demand for the VCO to shift from 8 to 10 GHz frequency. This linearizer has a transient response lasting for a period of about 60 microseconds. The magnitude of the initial oscillations produced a peak-to-peak frequency modulation of approximately 60 MHz on the 10 GHz carrier.

Figure 14b shows the response of the exponential function to the same step signal and the linearizer output has reached a fixed voltage in about 3 microseconds. No significant frequency modulation was observed on the carrier signal 3 microseconds after the step was applied.

These results demonstrate that using the wide-band exponential function generator, not only is intra-pulse FM reduced but also many radar signals at different frequencies can be generated per unit time because of its fast settling time.

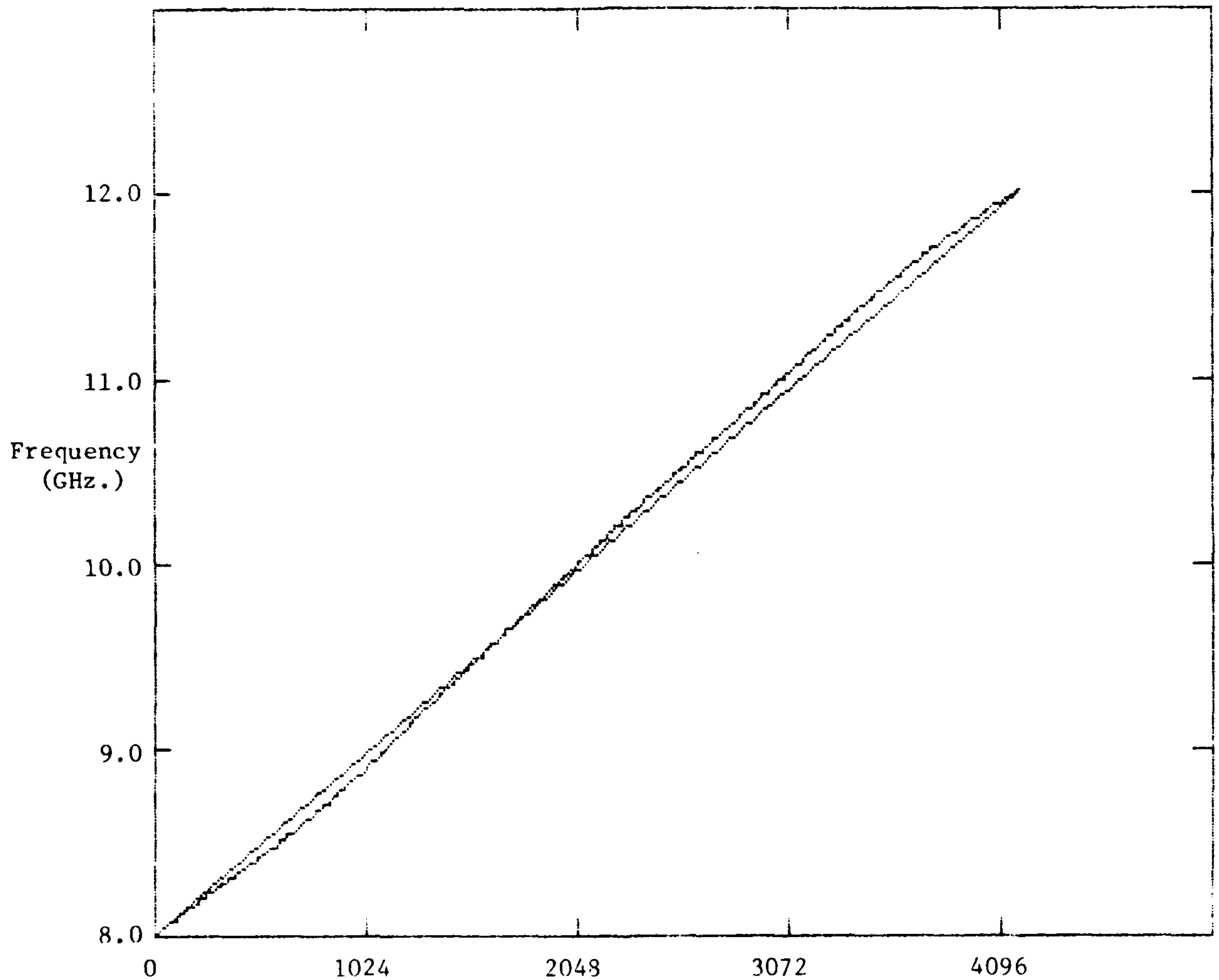


Fig. 7 Actual Linearized VCO

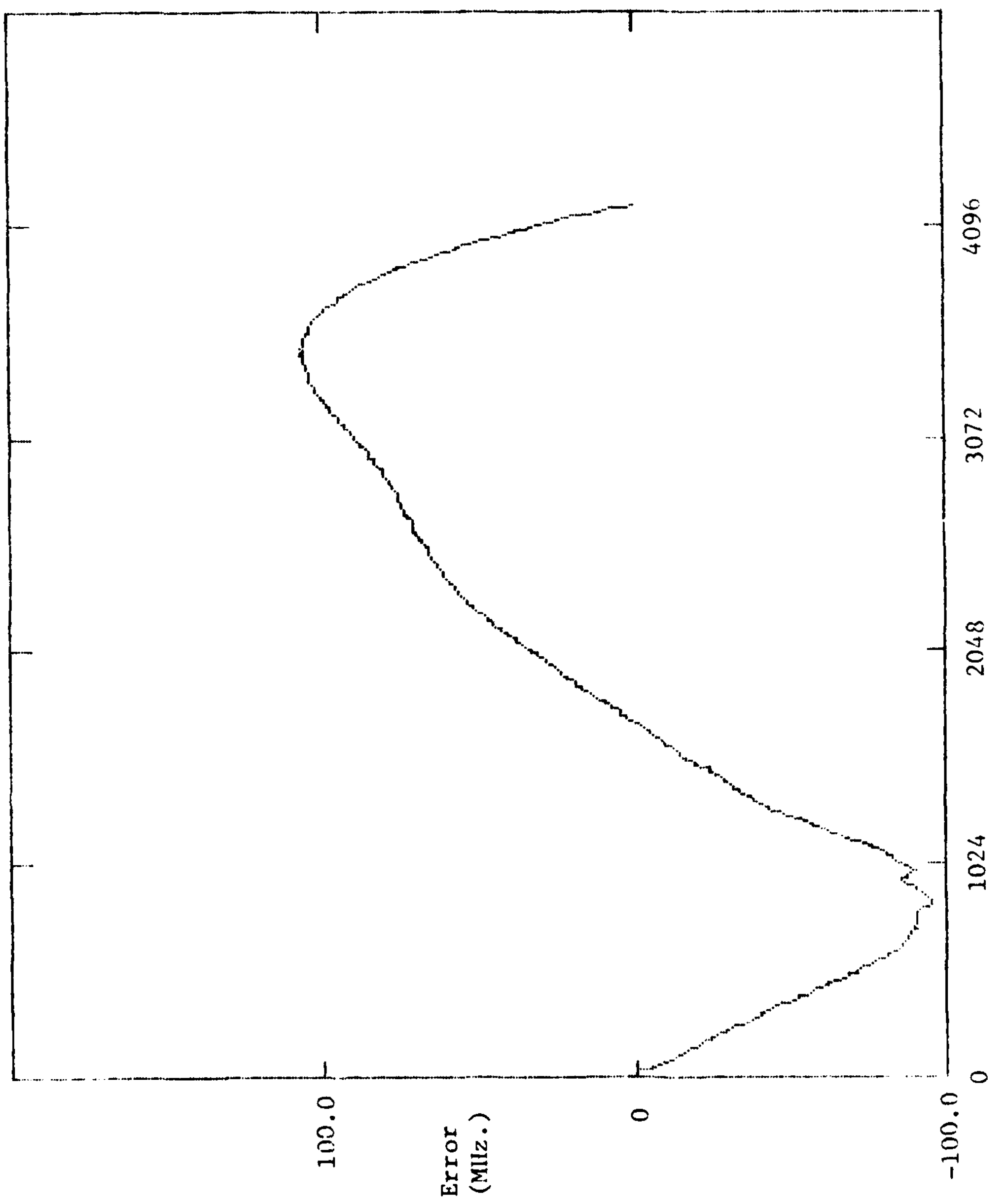


Fig. 8 Actual Linearized VCO - Error

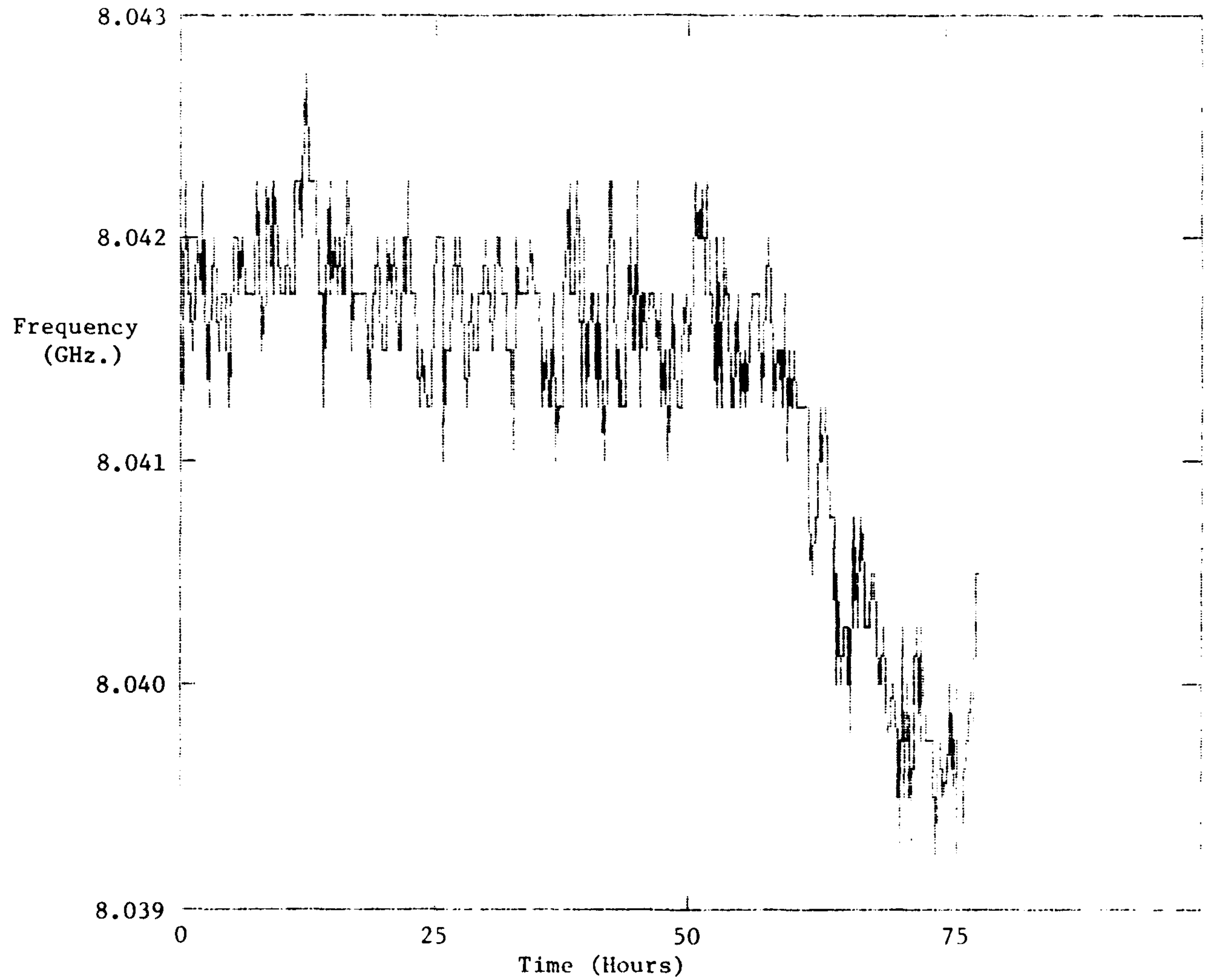


Fig. 9 Linearized VCO Long Term Frequency Stability (8 GHz.)

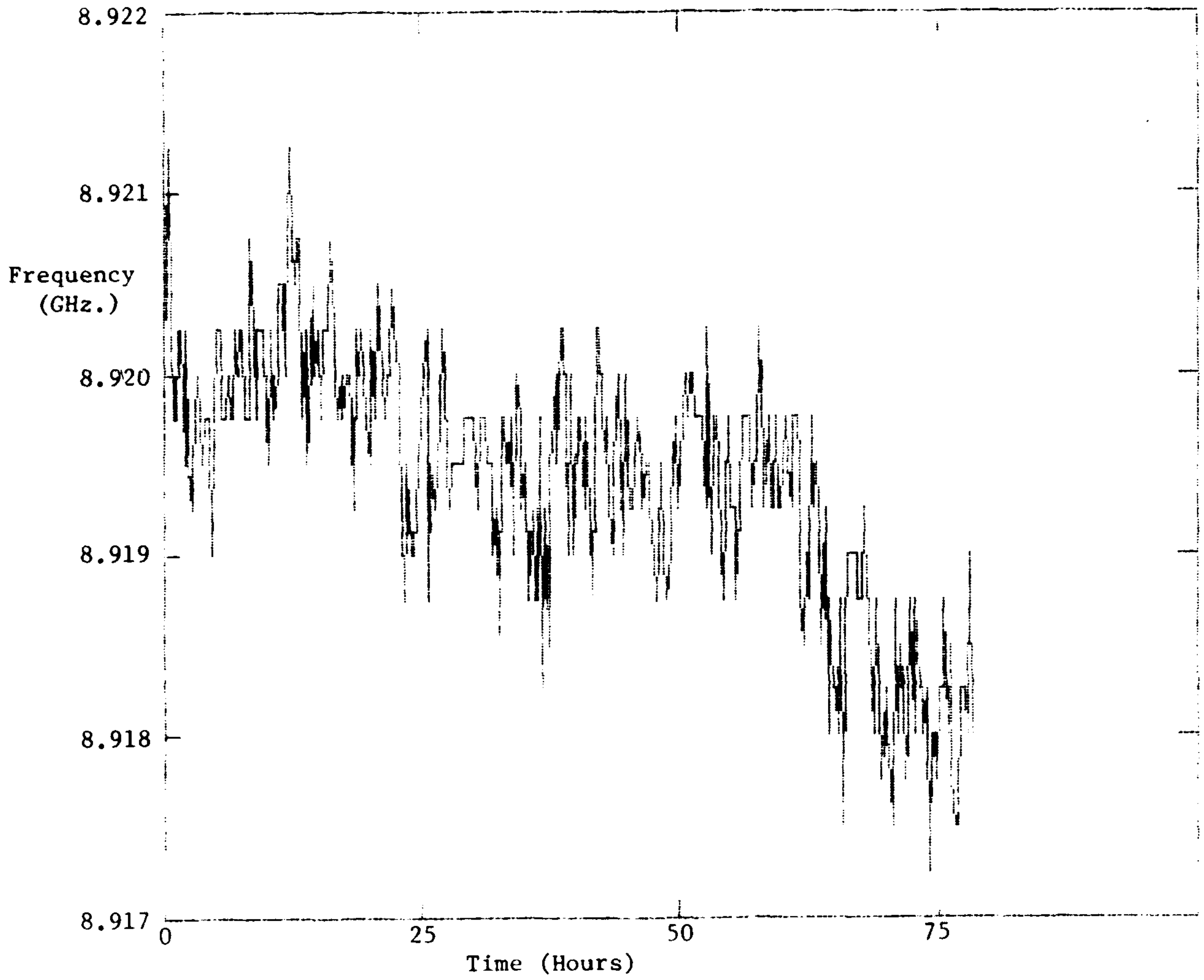


Fig. 10 Linearized VCO Long Term Frequency Stability (9 GHz.)

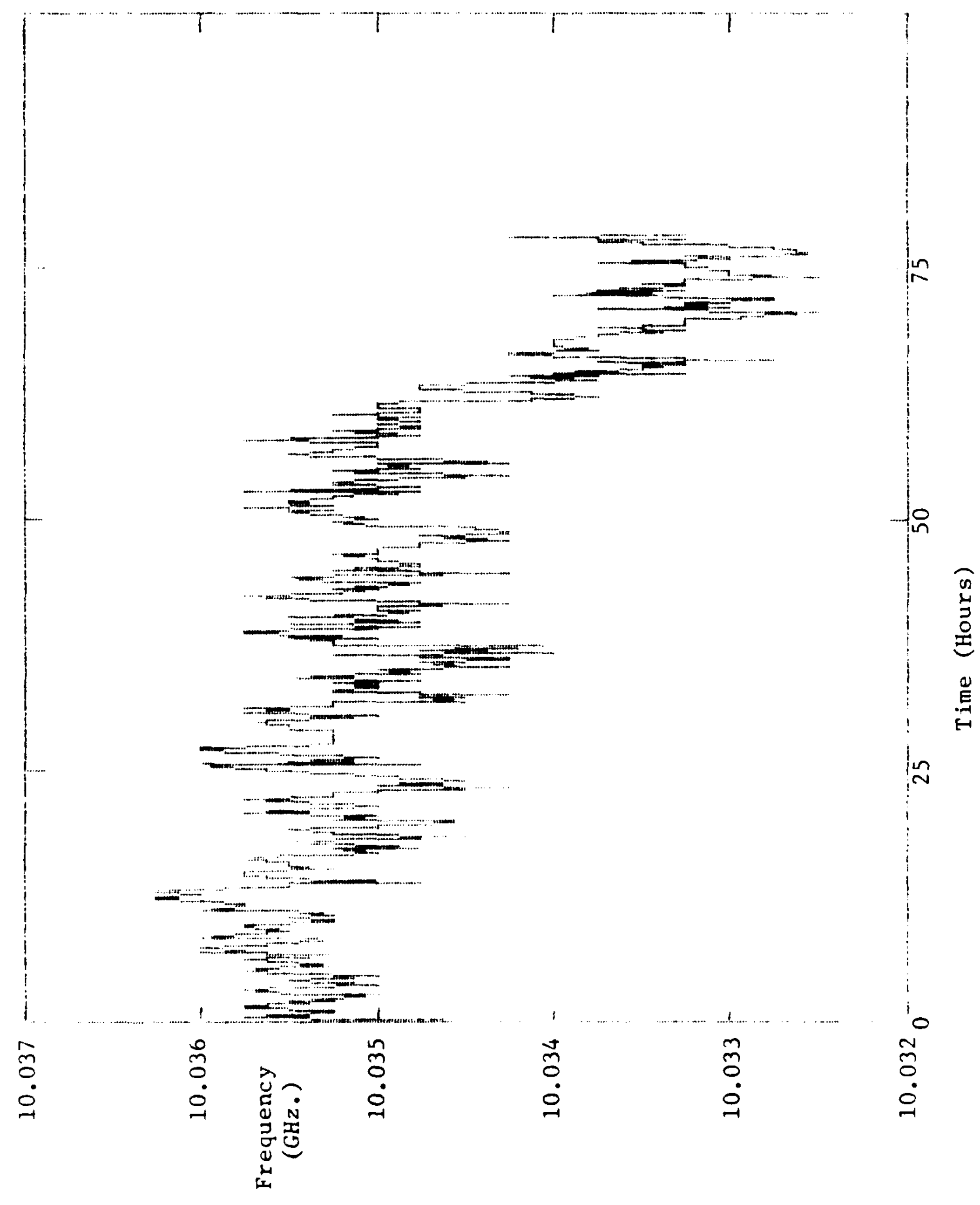


Fig. 11 Linearized VCO Long Term Frequency Stability (10 GHz.)

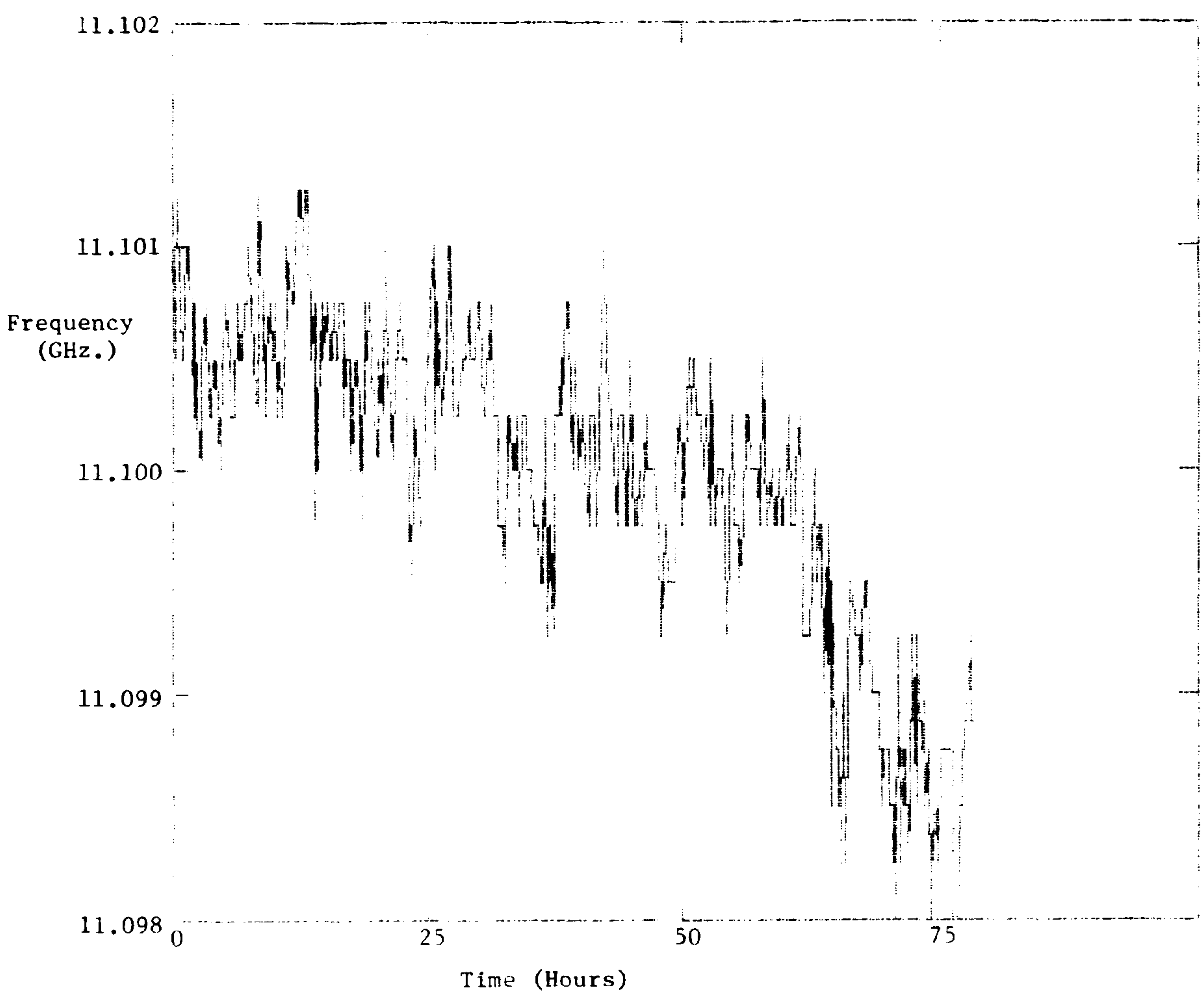


Fig. 12 Linearized VCO Long Term Frequency Stability (11 GHz.)

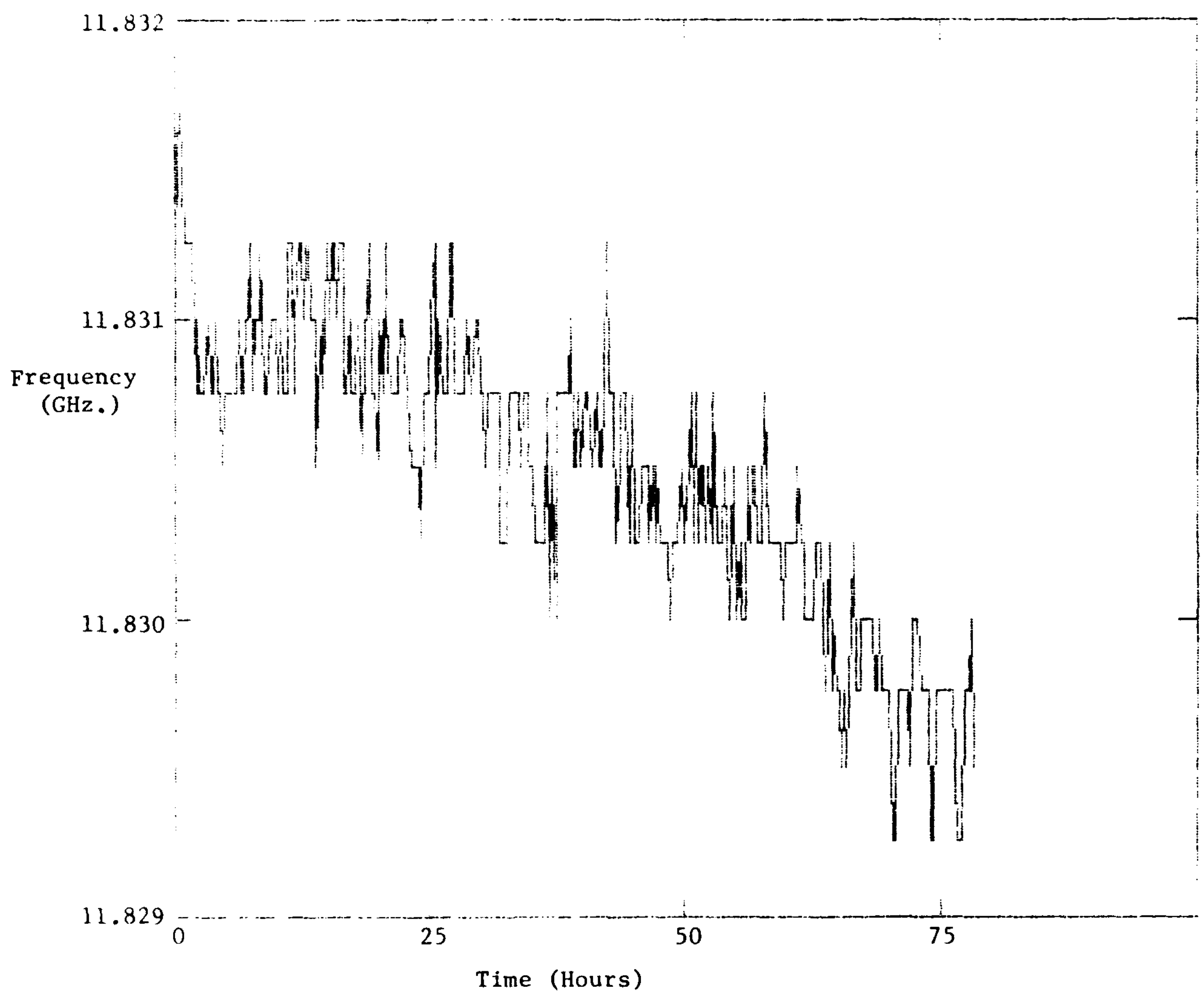
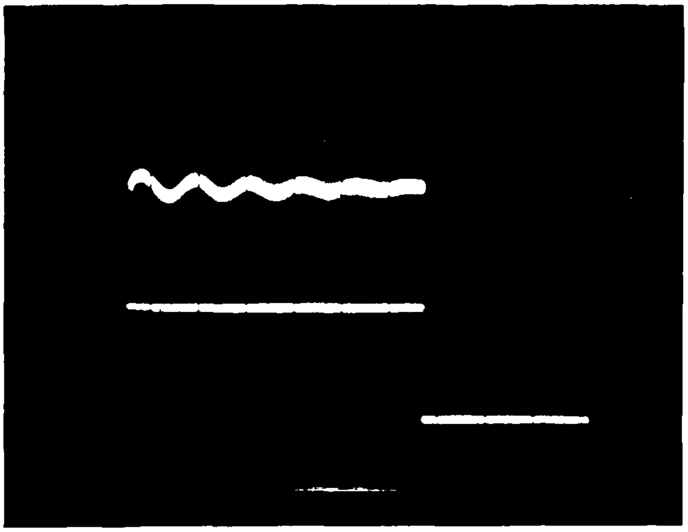
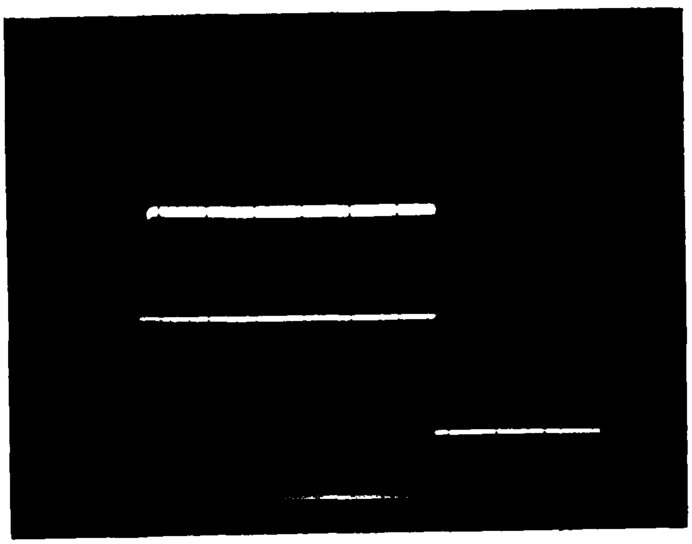


Fig. 13 Linearized VCO Long Term Frequency Stability (12 GHz.)



14a) Linear Approximator



14b) Exponential Functions

Fig. 14 Response of Linear Approximator and Exponential Function Linearizers - Time base 10 μ/div., vertical scale 0.5 volts/div.

4.0 CONCLUSIONS

The exponential linearizer permits the VCO to respond to the demand for a given frequency in a few microseconds. This is an important factor since one VCO can then be used to generate a large number of radar signals on different frequencies per unit time.

In addition, the exponential linearizer provides a method to achieve a first-order linear approximation to the frequency versus voltage characteristic of many types of VCO's. The discontinuities generated by the piecewise linearizer are avoided which otherwise can be of considerable concern when generating linear frequency modulated or chirp radar signals.

The accuracy achieved with the exponential linearizer is competitive with piecewise linearizers and it is relatively simple to design and adjust for optimum performance.

To achieve 0.05% frequency set-on accuracy, whether using piecewise or exponential linearizers, the final frequency correction uses digital techniques. A computer-controlled calibration procedure is used similar to the method described herein and the residual error data is stored and then used to correct each frequency as demanded when the radar signal scenario is selected and run.

5.0 REFERENCES

1. Millman & Halkias, "Electronic Devices and Circuits", McGraw-Hill 67-16934, 1967.

2. Stark, "Introduction to Numerical Methods", The MacMillan Company, 77-85773, 1970.

APPENDIX A

VCO FUNCTION MEASUREMENT METHOD

Measurement Method

VCO data is obtained under the control of a "measurement microprocessor" as shown in Figure A-1. Commanded frequencies are converted to analog voltages, using a 12 bit D/A converter where a D/A count of 0 to 4095 represents an output voltage range of 0 to 10 volts. The D/A output can be connected to the input of either the linearizer under test or directly to the VCO to obtain the non-linearized VCO function shown in Figure 1 of the report. A frequency counter is employed to measure the frequency of the CW signal from the VCO. The counter performs a measurement in approximately 50 msec with a frequency resolution of 0.25 MHz.

Measurement Process

The measurement process is accurately timed such that repeatable measurements can be obtained. Initially, the D/A is set to a count value of zero and for each measurement event, the following steps are executed:

1. The D/A is tuned to some requested frequency.

2. The frequency counter is directed to make a measurement.

3. After the measurement delay of 50 msec, the D/A is tuned back to the base frequency (a D/A count of 0).

4. An intra-pulse delay time is initiated (programmable from 1 to 250 msec).

5. Upon the intra-pulse time-out, the process is repeated for some other test frequency.

The intra-pulse delay time is used to simulate the effect of sharing the VCO among several emitters. During times where no emitter activity is present, the VCO is normally tuned to the base frequency.

VCO frequency data is collected in groups, where a group is defined as an increasing sequence of programmed frequencies beginning at a D/A count of zero. Each frequency in the sequence is separated by a specified ΔF frequency increment until the highest possible value is measured. A specifiable group delay time is then initiated and upon time-out, the next group of measurements is taken. Group delay times of 1 to 65,000 seconds are possible.

Acquired data is transferred to a host computer for permanent storage and detailed analysis.

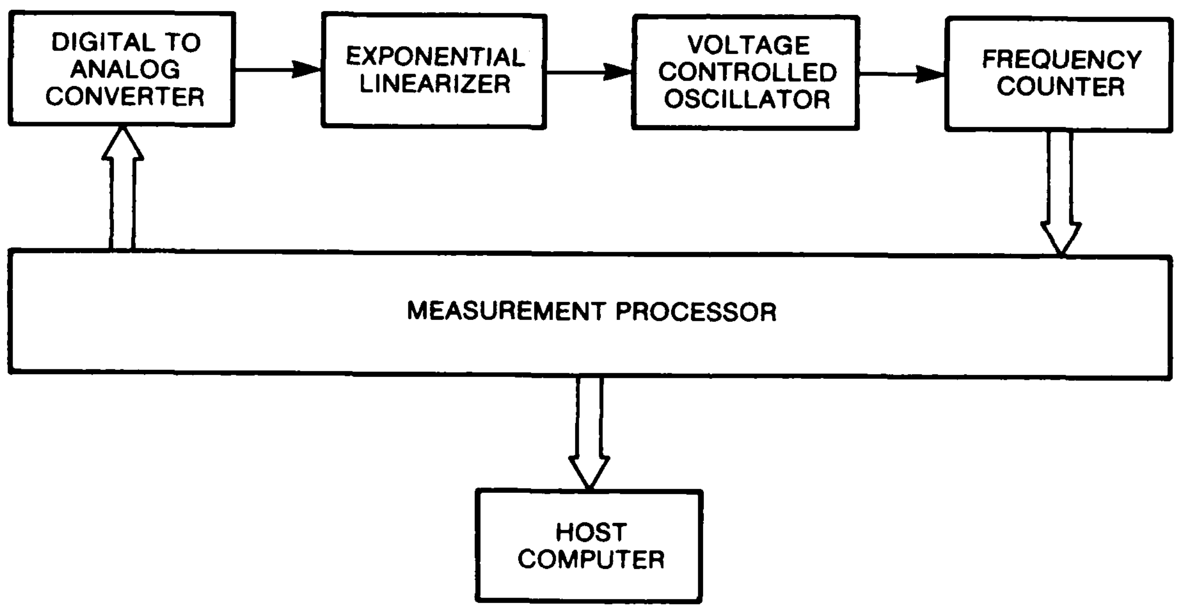


Fig. A-1 Experimental Measurement Set-up

A P P E N D I X   B

EXPONENTIAL LINEARIZER THEORETICAL DERIVATION

VCO Function

In order to determine the gain characteristic of a linearizer using the technique outlined in Appendix A, it is necessary to measure the exact response of the VCO to all possible input voltage values. Since a 12 bit D/A converter is employed, there are 4096 possible set-on frequencies. Experimental data was collected using a ΔF value of 1.

Inverse VCO Function

The input voltage (v) to the linearizer is derived from a D/A converter.

Let the gain characteristic of the linearizer be h(v), therefore, one may express the VCO output frequency as:

$$F = G\,[h(v)] \qquad (1b)$$

where: G, relates the VCO frequency to the initial voltage, V, and includes the effect of the linearizer gain and VCO characteristic.

In all further discussion, the voltages applied to the linearizer and the VCO are considered in D/A count units, where v is an integer value which ranges from 0 to 4095.

It is required that some h(v) be found such that:

$$F = a_o + a_1 v \qquad (2b)$$

where: a_o and a_1 are some set of constants that connect the end points of the curve, as shown in Figure 1 of the report.

Given the measured VCO function data set, for some v (taken as any of 4096 D/A values), equation 2b is evaluated and the data set is searched for the corresponding frequency element. The associated input D/A value is therefore the required h(v).

Exponential Curve Fit

Given the data set (ref. Figure 1), where the i'th sample is defined as (i, C_i), assume a best fit can be obtained by:

$$C_i = a\,(\exp(b_i)-1) \qquad (3b)$$

where: C_i is the i'th fitted value
a and b are constants
i is the i'th input integer value

then the i'th squared error is:

$$s_i^2 = (C_i - a\ (\exp(b_i)-1))^2 \qquad (4b)$$

Given that the end points C(4095) and C(0) are made equal to the data set values C(4095) and C(0), a least squares fit can be performed on b as follows:

$$\frac{\partial s^2}{\partial b} \sum_{i=0}^{4095} (C \ - a\ (\exp(b_i)-1))^2 (a\ i\ \exp(b_i)) = 0 \qquad (5b)$$

where for some b, the constant, a, is defined as:

$$a = 4095/(\exp(4095b)-1) \qquad (6b)$$

Defining the upper end point as C(4095), then the lower end point is automatically connected for i = 0.

Solving equations 5b and 6b numerically:

$$a = 0.078839 \text{x} 4095$$

$$b = 2.616229/4095$$

where a and b are shown normalized to the full scale value of i.

The actual and fitted curves are shown in Figure 3 of the report. The error curve shown in Figure 5 indicates that a relatively good fit can be obtained with a maximum deviation of about 30 MHz or 0.3% at mid-band frequency.

System Error

The curve fit problem outlined above was performed on the required linearizer gain characteristic. Although the resultant least squares error has been minimized on that curve, the "system" error should be considered where the system is composed of the combination of the linearizer and VCO.

Recall that equation (1b) describes the system frequency versus input voltage function and now that h(v) is known, values of frequency can be plotted against v. The error curve, Figure 5 in report, shows an almost equal error variation about the zero error axis, indicating that the original fit on the required gain characteristic was reasonable.

APPENDIX C

EXPONENTIAL FUNCTION GENERATOR HARDWARE REALIZATION

Exponential Function Generator

Conceptually, the exponential function generator is based on the current/voltage relationship of a diode. In the circuit diagram shown in Figure 6, the exponential function generator is composed of a matched differential transistor pair (Q1 and Q2). The collector current of Q1 is made constant by U2. The input is v2 and the output is i2. U3 converts i2 to Vout and U1 performs an inversion and offset of the input signal Vin.

The current/voltage relationship of a diode is given by:

$$i = io\ (\exp(v/(n\ Vt)) - 1) \qquad (1c)$$

where: io is the reverse leakage current of the diode
v is the voltage applied across the junction
n is 2 for silicon

and
$$Vt = T/11{,}600 \qquad (2c)$$

where: Vt is the "volt equivalent of temperature"
T is the temperature in degrees Kelvin.

Assuming that $\exp(v/(n\ Vt)) >> 1$ for a forward biased diode, replacing $1/(n\ Vt)$ by a constant k and assuming some constant ambient temperature:

$$i = io\ \exp(k\ v) \qquad (3c)$$

Assuming that the current gains and reverse leakage currents, hfe and io, respectively, in the differential pair in Figure 6 are matched, the currents i1 and i2 are defined as:

$$i1 = hfe\ io\ \exp(k\ (v2 - v3)) \qquad (4c)$$

$$i2 = hfe\ io\ \exp(\ k\ (-v3)) \qquad (5c)$$

From equations 4c and 5c, (hfe io) can be extracted such that:

$$hfe\ io = i1\ \exp\ (-k(v2 - v3)) = i2\ \exp\ (-k(-v3)) \qquad (6c)$$

Solving equation 6c for i2 yields:

$$i2 = i1\ \exp\ (-k\ v2) \qquad (7c)$$

where: i1 is a constant due to U2.

Inversion and offset of Vin is performed by U1 and associated resistors. Referring to Fig. 6, V1 is attenuated by the R5 and R6 networks. Assuming an input voltage range of 10 volts, V2 in terms of Vin can be written as:

$$v2 = k2\ (10 - Vin) \qquad (8c)$$

where: $k2 = R6/(R5 + R6)$

and hence i2 in terms of Vin can be obtained from equation 7c and 8c:

$$i2 = i1 \exp(-k\,(k2\,(10 - Vin)))$$

or

$$i2 = i1 \exp(-10\,k\,k2) \exp(k\,k2\,Vin) \qquad (9c)$$

The output amplifier, U3, sums an offset current (ios) with i2 and converts the result to Vout by:

$$Vout = R8\,(i2 - ios) \qquad (10c)$$

and when combined with equation 9c yields:

$$Vout = R8\,i1 \exp(-10\,k\,k2) \exp(k\,k2\,Vin) - R8\,ios$$

which can be written in the form:

$$Vout = a\,(\exp(b\,Vin) - \ell) \qquad (11c)$$

where: $a = R8 \exp(-10b)$
$b = k\,k2$
$k = 1/(n\,Vt)$
$k2 = R6/(R5 + R6)$
and $\ell = R8\,ios/a$

To obtain the correct form of the exponential function we set

$$\ell = \frac{R8\,ios}{a} = 1$$

Equation 11c is of the desired form as used in the previous section assuming the matched conditions as noted and a constant ambient temperature.

Circuit Realization

The resistor values in the circuit of Figure 6 are determined based on reference voltages of +/- 12.0 volts for +Vref and -Vref respectively. Referring to equation 8c, U1 will provide the required function (10-Vin) if we set:

$$R1 = R3 = 10\text{ K}$$

and

$$R2 = 12\text{ K}.$$

In the following derivation, the equations of interest are:

$$V0 = a\,(\exp(b\,Vin) - 1) \qquad (12c)$$

where

$$a = R8\,i1 \exp(-10\,b) \qquad (13c)$$

$$b = k\ k2 \tag{14c}$$

and

$$R8\ ios/a = 1 \tag{15c}$$

where: $k = 1/(n\ Vt)$
$n = 2$ for silicon
$Vt = T/11{,}600$

From the results of the curve fit and normalizing the voltage range to 10 volts,

$$a = 0.78839$$
$$b = 0.261623$$

and selecting R4 to be 3.3 K,

$$i1 = 3.634 \text{ ma., a constant, due to U2.}$$

From equation 13c,

$$R8 = 2.9687 \text{ K.}$$

Assuming a fixed ambient temperature of 70 degrees Kelvin, equation 14c yields:

$$k2 = 0.015471$$

and for R6 = 100 ohms, R5 = 6.363706 K.

From equation 15c, R9 = 45.3352 K, to obtain the required value of offset current ios.

Exponential Function Generator - Detailed Circuit

In the detailed circuit diagram of Figure C-1, U1 performs the input inversion and offset, U2 maintains a constant collector current through Q1, Q1 and Q2 form the differential pair and U4 provides the current-to-output voltage conversion.

In order to maintain the substrate of Q1 and Q2 at approximately 70 degrees Celsius, Q3 is used as a temperature sensor. As noted for the RCA CA 3046, Vbe varies as -1.9 mv per degree C, therefore the circuit of U5 and Q6 drives Q4 and Q5 to heat the substrate such that Vbe through the divider R10, R11, results in a null input to U5.

C1 and C2 provide additional frequency compensation to U2 and U4 respectively such that a 0.5 microsecond rise time can be achieved without ringing. C3 prevents temperature "hunting".

Metal film resistors are used as noted to minimize temperature drift.

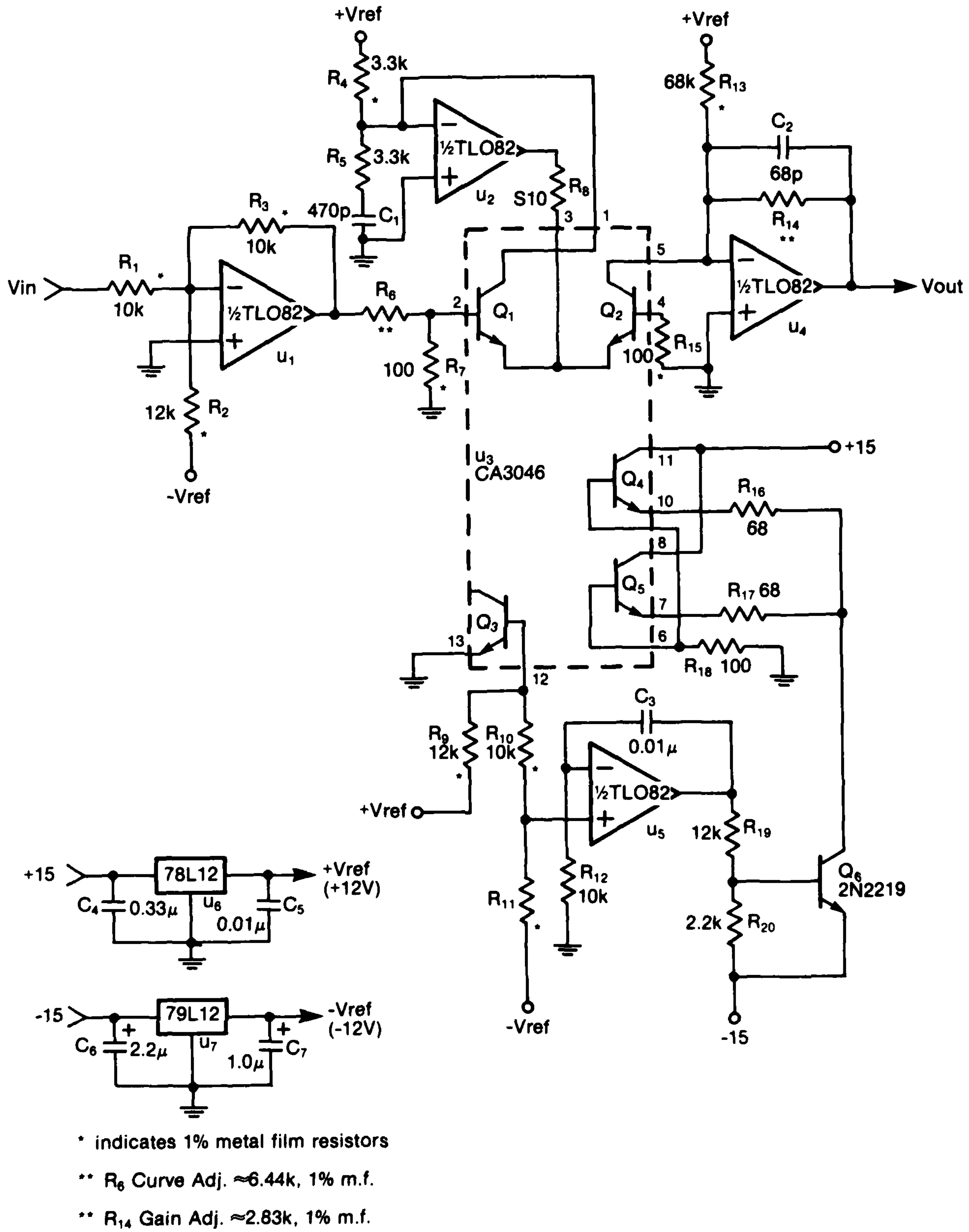


Fig. C-1 Exponential Function Generator - Circuit Diagram

Output Driver Amplifier

To achieve the full tuning range, the VCO requires an input range of approximately 6 to 45 volts. The circuit of Figure C-2 transforms the linearizer output range of 0 to 10 volts to the required VCO drive. Due to the limited unity gain bandwidth of Q1, the circuit of U1 provides a fixed gain with C1 used for additional frequency compensation.

The gain of the driver amplifier is given by:

$$G = 1 + (R6/(R3 + (R4\ R5)/R4 + R5)) \qquad (16c)$$

and is set to approximately 4.5. The overall gain is accurately set by R14 in Figure C-1. The overall offset is controlled by P5, shown in Figure C-2.

Calibration

Before using the calibration procedure outlined below, the linearizer should be powered up and allowed to stabilize for approximately one hour. Using a temperature probe and thermally conductive paste, measure the case temperature of U3 in Figure C-1. A value of approximately 65 degrees C or higher should be found and if not, adjust R11 to obtain the correct temperature. The differential pair substrate must operate higher than the highest expected ambient temperature.

Three adjustments are required to calibrate the linearizer - VCO system. The procedure is interactive and assumes that sufficient warmup time has expired. Three accurately known input voltages are required to tune the VCO to the lowest, mid and highest frequencies. These are respectively 0, 5.0 and 10.0 volts. Initially, trim-pots can be used in place of R6 and R14 in Figure C-1 and R5 in Figure C-2 with initial settings as indicated.

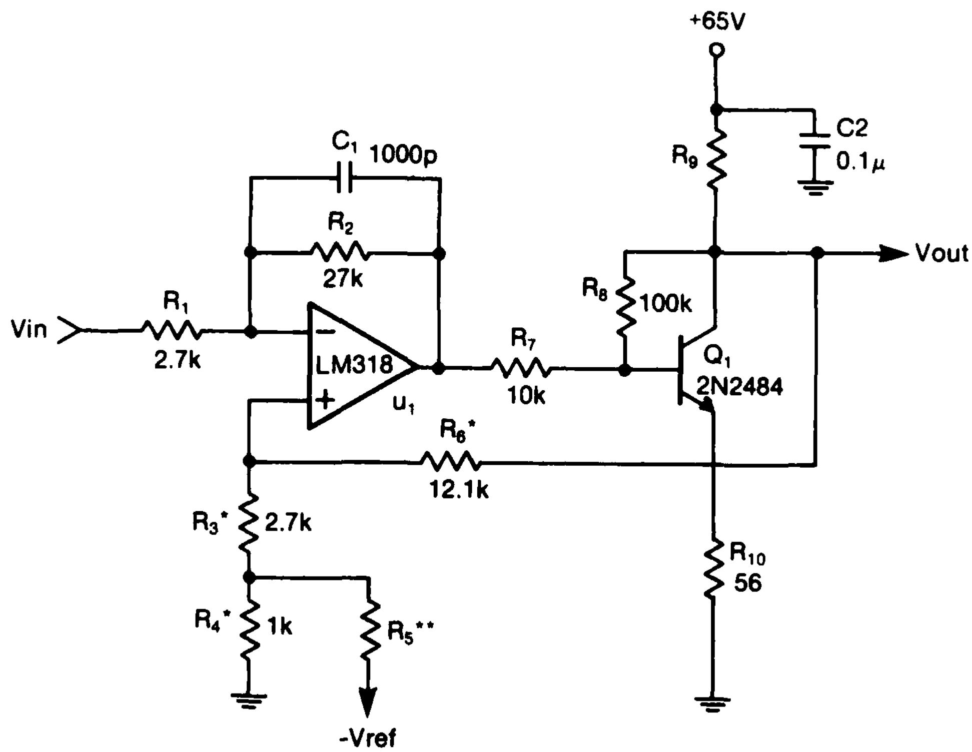
Assuming an X band VCO, the corresponding three frequency values should be 8.0 GHz, 10.25 GHz and 12.0 GHz. Using the gain and offset adjustments, perform the following steps:

1. Set the input to 0 volts and adjust the gain pot for 8.0 GHz.

2. Set the input to 10.0 volts and adjust the offset pot for 12.0 GHz.

3. Repeat steps 1 and 2 until the correct frequencies are obtained.

With the end-points correctly set, input 5.0 volts and adjust the curve adjustment pot for 10.25 GHz. Then input 0 volts and adjust the gain pot for 8 GHz. Alternate these two adjustments until the correct frequencies are obtained.



* indicates 1% metal film resisters

** R_5 offset adj. 3.92k, 1% m.f.

Fig C-2 VCO Driver Amplifier

Repeat steps 1, 2 and 3 and then perform the curve adjustment if required. A few of the above iterations will be required in order to achieve an accurate result.

The resistor values obtained after calibration can then be fixed with metal film networks to minimize thermal drift. Those indicated in Figures C-1 and C-2 were obtained from the above procedure.

It is assumed that end-point adjustments in trim-pot form are available within the D/A module and would be subsequently set to provide a slightly greater frequency range than the 8 to 12.0 GHz obtained from the above calibration procedure. Any further end-point corrections and of course the final error correction can then be removed digitally.

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THE DEVELOPMENT OF A HIGH SPEED EXPONENTIAL FUNCTION GENERATOR FOR LINEARIZATION OF MICROWAVE VOLTAGE CONTROLLED OSCILLATORS (U)

TECHNICAL NOTE

MICKEAL, James F., RENAUD, Jean-Jacques, MCMILLAN, Myles R.

OCTOBER 1985	40	2
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Unlimited

DREO

Voltage Controlled Oscillators used in radar signal simulators usually employ piecewise approximation linearizers to compensate for non-linear frequency versus voltage tuning characterisitics. A linearizer was developed which closely approximates an exponential (frequency/voltage) relationship found in many VCO's. This linearizer uses the forward biased (voltage/current) characteristic of a p-n junction to provide exponential linearization in a simple, thermally-stable, wide band circuit.

UNCLASSIFIED

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KEY WORDS

VCO
VOLTAGE CONTROLLED OSCILLATORS
EXPONENTIAL
LINEARIZER
ANALOG CIRCUIT
RADAR SIGNAL SIMULATORS
MICROWAVE

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